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Technology development and application of solar energy in desalination: MEDRC contribution

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ABSTRACT

Desalination has become one of the sources for water supply in several countries especially in the Middle East and North Africa region. There is a great potential to develop solar desalination technologies especially in this region where solar source is abundantly available. The success in implementing solar technologies in desalination at a commercial scale depends on the improvements to convert solar energy into electrical and/or thermal energies economically as desalination processes need these types of energies. Since desalination is energy intensive, the wider use of solar technologies in desalination will eventually increase the demand on these technologies, making it possible to go for mass production of photovoltaic (PV) cells, collectors and solar thermal power plants. This would ultimately lead to the reduction in the costs of these technologies. The energy consumed by desalination processes has been significantly reduced in the last decade meaning that, if solar technologies are to be used, less PV modules and area for collectors would be needed. The main aspects to be addressed to make solar desalination a viable option in remote location applications is to develop new materials or improve existing solar collectors and find the best combinations to couple the different desalination processes with appropriate solar collector. In the objective to promote solar desalination in MENA, the Middle East Desalination Research Center has concentrated on various aspects of solar desalination in the last twelve years by sponsoring 17 research projects on different technologies and Software packages development for coupling desalination and renewable energy systems to address the limitations of solar desalination and develop new desalination technologies and hybrid systems suitable for remote areas. A brief description of some of these projects is highlighted in this paper. The full details of all these projects are available the Center's website.

Contents

1. Introduction

Desalination of brackish and seawater has become one of the viable solutions for the water shortage in the Middle East and North Africa (MENA) region [1]. Desalination processes are energy intensive. Some of the countries of the region are blessed with conventional sources of energy, oil and gas, while others are not. In

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the oil rich countries the water problem is solved by large desalination plants powered with conventional energy. In rural areas, one option is to develop small to medium scale desalination units that can treat brackish or seawater [2]. In the non-oil producing countries, the small-scale units could use solar energy in order to limit the use of expensively purchased fossil fuels.

Solar energy coupled to desalination offers a promising prospect for covering the fundamental needs of power and water in remote regions, where connection to the public electrical grid is either not cost effective or not feasible, and where the water scarcity is severe. The MENA region has outstanding solar resources. This can be captured for use either by photovoltaic (PV) devices or by direct absorption as thermal energy. The distribution of this resource is more evenly spread over the entire region than other renewable energy resources, which tend to be site specific. Vast areas are available for this resource to be utilized. The long-term development of this on a large scale will hinge on technical developments that will reduce the cost of electricity generated by PV or by solar thermal power plants [3]. Although solar desalination systems cannot compete with conventional systems in terms of the produced water cost, they remain applicable to certain areas and are likely to represent more widely feasible solutions in the near future [4]. Environmental restrictions are also in favor of using renewable energies for different applications as they are more environmentally friendly technologies.

Worldwide, several solar desalination pilot plants have been installed and the majority has been successful in operation. Virtually all of them are custom designed for specific locations. Recently, some larger desalination plants using PV cells, connected with existing electricity grid, were built mainly in Australia and Spain [2]. Solar desalination is an important challenge and much useful work has been done [5]. However, in order to provide practical viable plants, much more remains to be done. Operational data and experience from these plants can be utilized to achieve higher reliability and cost minimization.

Middle East Desalination Research Center (MEDRC) has concentrated on various aspects of solar desalination in the last twelve years by sponsoring 17 research projects on renewable energies, in which four software packages with different levels of accuracy which are available on the center's website were developed [6]. In this paper, a brief description of these projects and the different technologies in use are highlighted.

2. MEDRC efforts to promote solar desalination in MENA region

In order to decrease the cost of solar desalination and make it technically viable, the following aspects have to be addressed.

1. Develop new types of solar collector systems or improve the existing systems to enhance the efficiency and reduce the cost.
2. Develop new desalination technologies or improve the existing ones to enhance the efficiency and make them suitable for remote location applications.
3. Develop methods to couple the different desalination processes with appropriate solar collectors with appropriate energy storage for low-cost water production. This could be achieved through optimal process and equipment designs.

MEDRC sponsored 17 projects to address some of the above issues [6]. They are categorized into development–improvement of desalination technologies, humidification–dehumidification (HD), Multi Effect Distillation (MED), Reverse Osmosis (RO), VARI-RO, Electrodialysis (ED), seawater greenhouse, and software packages.

2.1. Desalination processes based on humidification/dehumidification

In the HD process solar energy is used to heat the feed saline water to desired temperature, about 70 °C, using a solar collector. The heated feed water then passes over an evaporating surface (evaporator) in a counter current direction to air. The air thus gets humidified. The humid air is then passed through a condenser to produce fresh water by dehumidification process. There are two water cycle technologies: closed air and open water cycle and open air and closed water cycle. The Center sponsored the following five projects on this topic to explore the technology.

1. A comprehensive study of solar desalination with HD cycle.
2. Hybrid fossil/solar heated Multi-Effect-Still.
3. Small scale thermal water desalination systems using solar energy or waste heat.
4. Development and analysis of the diffusion driven desalination (DDD) process.
5. Experimental and theoretical studies on integration of new PCM-based components in solar desalination.

In the first project a comprehensive literature review of the solar HD techniques and the various desalination units based on this principle has been carried out. A mathematical model of solar desalination process based on HD cycle was developed and simulation studies were carried out to study the effect of various system parameters like solar collector area, humidifier surface area and condenser surface area and system operating parameters like feed water flow, temperature, etc., on system performance. These simulation results are useful in designing the state of the art of commercial scale HD systems. A comprehensive review of reported capital and operating costs of various solar desalination processes was also conducted. Cost figures reported in the literature encouraged more to conduct research to improve the HD process and thus a couple of projects were sponsored on this subject area.

A major improvement in solar still design is possible through the multiple use of the latent heat of condensation in the still. MEDRC thus sponsored a project on "Hybrid Fossil/Solar Heated Multi-Effect-Still". In this project a four effect still was designed with 4 m^2 each of evaporator and condenser surfaces. In this unit, heat is supplied only to the first cell by a heat exchanger to the heat transfer fluid test facility to simulate a solar collector cycle. Water is evaporated in the second effect as it trickles over a metallic surface heated by the condensation of the vapor from the first effect. This allows the utilization of the latent heat at different levels. The energy of the last condensation surface is absorbed by the cooling cycle, connected to a wet cooling tower via a heat exchanger. The designed capacity of this pilot was 8.7 $kg/m^2/h$, with an energy input of 2.0 kW/m^2 and the GOR of 3. This unit was operated with hot water at a constant temperature of 96 °C. But, under such high operating conditions, the evaporation and condensation are very efficient but for long-term operation it is not practical due to scale formation. Furthermore, if a solar collector is used to drive the desalination unit then its collection efficiency will drop at high temperature. The GOR in the experimental unit was about 2. This low GOR was attributed to heat losses from the unit to the surroundings due to improper insulation. Low GOR could also be due to improper stage arrangement and configuration.

The GOR was low and the principal investigator of this project recommended TAS system. We thus sponsored a project on "Small Scale Thermal Water Desalination Systems Using Solar Energy or Waste Heat" in which a pilot scale system of TAS was fabricated in Germany and built and operated in Oman to evaluate its performance for local climatic conditions (Fig. 1). The system and operating data of the pilot unit were measured over a period of

Fig. 1. Small scale thermal desalination system (MEH) using solar energy.

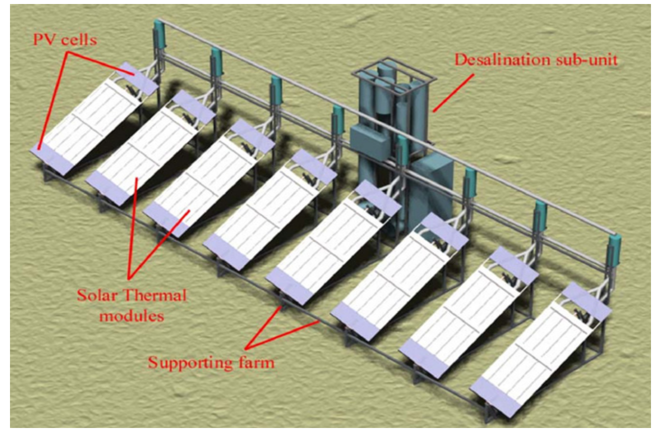

Fig. 2. Small solar MED desal unit.

one year. The performance of the system was good and it achieved the designed GOR. Measured data was used to develop steady state and dynamic models and these models were used in designing a commercial scale plants to be built in the region.

A Multi-Effect Humidification (MEH) desalination system which is based on the principle of HD of air by natural convection and using solar energy or waste heat as a source of energy was investigated in this project. Evaporation of seawater and condensation of water vapor from humid air take place in a single chamber at ambient pressure and at temperatures between 40 and 85 °C. It has high performance ratio between 4 and 6. The design is simple and requires less process control than conventional MED or MSF plants. The heat transfer surfaces for condensation were constructed from plastic materials and require little maintenance. The system is suitable for small-scale applications with 0.5–10 m^3/d distillate production capacity.

The main task and essential objectives of the project were verification and optimization of a simulation model for this solar thermal seawater desalination system by comparison of simulated and measured results obtained when performing the following steps:

- Design of a demonstration system based on the meteorological data of Oman, using an existing simulation program. This will allow calculation of the optimum component sizes for the collector field, storage tank and distillation unit.
- Utilization of the collected data in updating the simulation program to optimize future design of commercial units.
- Introduction of the process in MENA region. A dynamic simulation model programmed in a real-time simulation environment 'TRNSYS' was used to carry out the component design of the demonstration plant. High accuracy multi-channel measuring devices and a data logger have been applied over one year to obtain data relating to meteorological as well as system operation values. A long term operation has been proven that it is reliable for 24 h operation per day. The parameters that were applied during the design phase of the project appeared to be good estimates (<5% deviation between simulation and measured values). All the parameters of the system have been refined after evaluation of the data gained during the project's measuring time. They are the basis for future system design works. The results of the presented project are considered to be a further step towards successful commercialization of the MEH-desalination system.

HD processes reported in the literature show low thermal performance. In order to improve it, MEDRC sponsored a project on "Experimental and Theoretical Studies on Integration of New PCM-Based Components in Solar Desalination" which proposed to use Phase Change Materials (PCM) to address this issue. The PCM materials were enclosed in cubical or spherical plastic cans and these cans were packed in the evaporator and condenser columns to form porous beds. The heat transfer is better in porous beds than surface heat exchangers. In this project bench and pilot scale experiments were performed. Collected data from these test units were used for modelling the unit.

2.2. Multi effect distillation

Technically and economically it is more beneficial to couple conventional desalination processes like RO, ED, MED and MSF with solar energy systems. However, for remote location applications conventional RO, MED and MSF are not suitable. Therefore, MEDRC sponsored a project on "Small Solar MED Desalination Plant", in which MED process is modified to make it suitable for remote locations (Fig. 2). Conventional MED process uses horizontal falling film evaporation, which is more prone for scaling and fouling if feed water distribution is not proper on the horizontal tube bundle. In remote locations such operation is possible since they are operated by semi-skilled operators due to lack of human resources [1,7]. Hence, submerged tube bundle evaporation was used in the modified MED process. But submerged tube evaporation will have high scaling problems at higher temperatures. In order to overcome this problem, seedling technique was used to remove calcium and magnesium scales in the feed waters. Plasma coating was also used on the transfer surfaces to reduce scaling. A 12 effect MED pilot plant of 1000 L/day capacity was designed, fabricated in Russia and built and operated in Oman for a period of one year.

The main elements of the solar collector system are the tubular vacuum collectors and mirror concentrators which are installed in sixteen modules operating in the solar tracking mode. Solar collectors are filled with distilled water and produce steam, which provides thermal energy required for the operation of desalination system. The electricity demand of the plant was satisfied with 2 m^2 PV cells. The desalination system includes twelve submerged boiling effects connected in series with the last condenser being cooled with feed water and air. The plant was operated at top brine temperature of 100 °C and operated only during day time (9 h a day). The plant operates with 70–85% water recovery depending on the salinity of the feed water. Chemicals are not used for water disinfection or for anti-scale treatment. These tests proved that this plant can produce design quantity of desalinated water with rated power consumption without any scaling and fouling problems and can serve as an autonomous source of drinking water for small communities in remote locations without any external thermal and electrical energy supply or any additional cooling water.

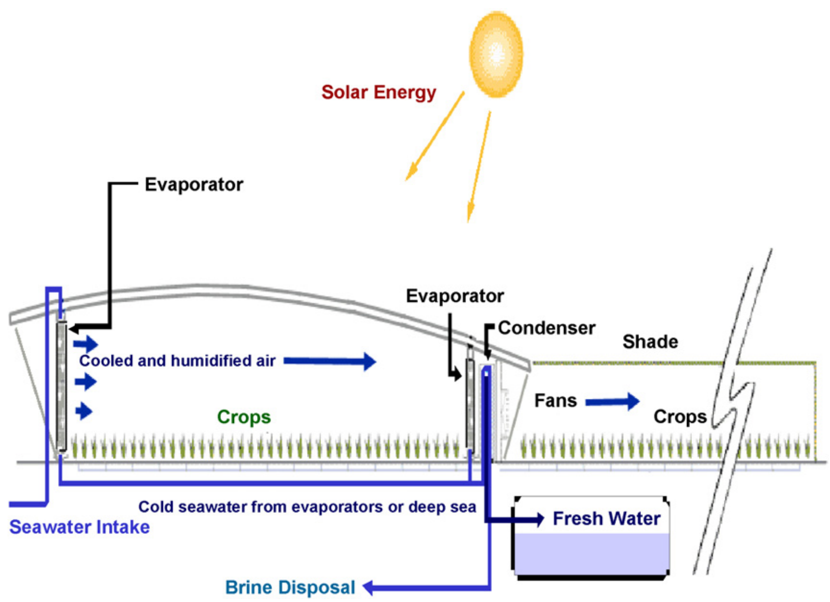

Fig. 3. Greenhouse unit.

2.3. Reverse osmosis and electrodialysis

Presently, RO is the more economical process due to developments in membranes, process and equipment designs [8]. In order to make it more efficient and compatible to run with solar energy, MEDRC sponsored a project "VARI-RO™ Solar Powered Desalting Study" to study the performance of various solar desalination systems. In this project a study has been conducted to show how desalination water cost can be improved by combining advanced technologies that are being developed for other uses. The objectives were to determine the technical viability and the potential to improve solar powered desalination using solar PV-EMD, solar dish collector – EMD, solar trough collector – DDE and solar dish collector – DDE.

MEDRC sponsored another project on "Design and Development of a Small Packaged Reverse Osmosis System Driven by a Hybrid Power Supply System". In this project a small RO system of 10 m^3/day (24 h operation) powered by PV/diesel generator was designed. The system was built in two containers for easy transportation and installation.

A project on "PV Powered Desalination: Matching Technology Options with Market Demands" was also sponsored by MEDRC. The main research objectives of the project were to perform technical and economic analysis and comparative study of RO and ED processes powered with PV and to develop guidelines for selection of RO or ED. RO as well as ED combined with PV are technically feasible options for brackish water desalination in remote locations. However, economic viability and selection of either RO or ED depends on site conditions. ED is better considering intermittent or fluctuating flux as a consequence of changes in solar source. ED also allows more than RO use of effective chemical cleaning for anti-fouling/scaling. For feed salinity of more than 1200–2000 ppm, RO is more economical than ED. This study also identified a limited number of product options and configurations offering potential promises for PV powered desalination in remote sites.

2.4. Seawater greenhouse

The concept of solar distillation within a glazed enclosure (solar still) dates back to more than 100 years, but the idea of combining it with the growth of crops in a controlled greenhouse environment is new. The seawater greenhouse is one of the more novel and effective HD systems that have been developed over the past decade [9]. The seawater greenhouse uses sunlight, seawater and air to produce fresh water and cool air, creating more temperate conditions for the cultivation of crops. The process recreates the natural hydrological cycle within a controlled environment. Surface seawater trickles down the front wall evaporator, through which air is drawn into the greenhouse. Dust, salt spray, pollen and insects are trapped and filtered out leaving the air pure, humidified and cool. Sunlight is selectively filtered by the roof elements to remove radiation that does not contribute to photosynthesis. This helps to keep the greenhouse cool while allowing the crops to grow in high light conditions. Air passes through a second seawater evaporator and is further humidified to saturation point. Saturated air passes through the condenser, which is cooled using cold deep seawater. Pure distilled water condenses and is piped to storage tank. Fans draw the air through the greenhouse and into a shaded house area.

MEDRC sponsred a project on "Seawater Greenhouse Development for Oman: Thermodynamic Modelling and Economic Analysis" to predict the performance of the seawater greenhouse for Oman climatic conditions using a thermodynamic model that is based on heat and mass balances (Fig. 3). In this project, thermodynamic and economic efficiencies of solar desalination systems were determined for various greenhouse-related parameters on desalination process. Simulation studies have shown that the dimensions of the greenhouse had the greatest overall effect on the water production and energy consumption. Low power consumption went hand-in-hand with high efficiency. A wide shallow greenhouse, 200 m wide by 50 m deep gave 125 m^3 per day of fresh water. This was greater than a factor of two compared to the worst-case scenario with the same overall area (50 m wide by 200 m deep), which gave 58 m^3 per day. Low power consumption went hand-in-hand with high efficiency. The wide shallow greenhouse consumed 1.16 kWh/m^3, while the narrow deep structure consumed 5.02 kWh/m^3. Total fresh water production for three different versions (temperate, tropical and oasis) was also calculated. The model results predict that the Seawater Greenhouse will perform efficiently throughout the year, but with measurable variations in performance between the alternative versions. It was found that water productivity can be improved but with greater energy consumption, and efficiency can be improved but with a small reduction in water output. From the results of the optimization study, values of

liters per square meter of floor space were calculated for different versions of the Seawater Greenhouse. Using the cost of the greenhouse structure and components, together with the value for the external area that could be supported by the surplus water were calculated. Based on the simulation study, a pilot scale Seawater Greenhouse was built and tested at Sultan Qaboos University in Oman. This pilot plant was operated over a period of one year. The results of this pilot plant operation clearly indicated that desalinated water produced by the greenhouse was much less than the design values and it was due to leakages and non-availability of low temperature cooling water. It is not difficult to control the leakages but to get low temperature coolant for condenser is difficult. One alternative could be the use of deep seawater (lower temperatures) and an other to improve the performance of the condenser.

The Center sponsored another project on "Greenhouse – State of the Art Review & Performance Evaluation of Dehumidifier" with the main objective to improve the performance of the condenser by developing new condenser configurations.

2.5. *Software packages*

The following projects on development of software packages that can be used for optimal coupling of desalination and renewable energy systems, optimization of process and equipment design, were investigated.

1. Matching Renewable Energy with Small Unit Desalination Plants: Literature Review & Analysis of the State of the Art of Renewable Energy & Small Unit Desalination Systems.
2. Matching Renewable Energy with Small Unit Desalination Plants: Development of a PC-based Decision Support System.
3. Development of a Logistic Model for the Design of Autonomous Desalination Systems with Renewable Energy Sources.
4. System Analysis of Renewable Energy Conversion Integrated with Desalination Processes.

In the first project literature survey has been carried out for the information required for developing "easy to use Decision Support System (DDS)" software. In the second project software package was developed based on heuristic approach using rules of thumb reported in the literature. This software allows the user to evaluate different desalination and renewable energy systems combination, develop feasible combination of desalination and renewable energy systems, design desalination and renewable energy systems for desired water demand and calculate the specific water cost produced by the system.

In the third project Hybrid-RO simulation software was developed. Hybrid-RO simulation software is based on a logistic modelling approach using the time-series technique. It simulates the performance of hybrid power supply system, which supplies the required power to RO plant and calculates the unit cost of water produced using the lifecycle cost analysis method. It helps in obtaining the least water production cost option by evolving optimum hybrid power supply system configuration and each component designs for exploiting wind and solar potential using time-series data of water demand and renewable sources. An energy balance approach is used within each time step. It provides the chance to the user to decide and examine several scenarios on the power supply system, Wind/PV/diesel, PV/diesel, wind/diesel, depending mainly on the RES potential of the location under study. Priority is given to the usage of renewable energy sources whereas diesel generator is mostly considered as a back-up system.

In the fourth project general purpose chemical process plant simulation software package, IPSEpro, was used. IPSEpro is a modular based package consisting of models for all the equipment that are encounter in the chemical process plants. The user can build the required process flow sheet of any chemical process plant using the equipment models available in the software and simulate the process for obtaining optimal operating conditions/equipment design. In this project, equipment models for various desalination process and renewable energy systems were developed and incorporated into the IPSEpro simulation software to facilitate the developed process flow sheet for any desalination process coupled with any renewable energy system. An economic analysis model based on life cycle cost was also included in the IPSEpro. This updated IPSEpro simulation package can be used to simulate any renewable energy driven desalination process and allow the user to calculate the unit water cost. Since license fee for using IPSEpro is high, executable modules for 12 process flow sheets which include most of the generally used flow sheets for coupling renewable energy and desalination systems. These 12 flow sheets are available for use by desalination community for simulation studies.

All the above projects and others including software packages along with other simulation and databank software packages developed in MEDRC projects as well as details of the principal investigators and research teams of these projects are available on MEDRC website www.medrc.org as downloadable report files for public use [6]. A detailed list of papers published, by the principal investigators and their respective research teams, in different journals are also available in the Center's website.

3. Conclusion

By supporting 17 research projects, MEDRC has contributed for the development of new technologies based on HD principle and for development of software packages for process and equipment design. Greenhouse desalination is an excellent technology to grow crops in arid regions and considerable amount of research is required to make it a viable option. All these projects are available on MEDRC website, www.medrc.org, as downloadable files for public use.

Other conclusions can be drawn as follows:

- Renewable energy systems have proven to be reliable. They are the technologies of the future and will play a role in future scenarios. It has great potential in MENA region due to availability of vast stretches of waste lands and high intensity of solar radiation.
- Presently it cannot be used for large scale applications due to technological and economic limitations.
- There is limited scope to decrease the energy consumption in commercial desalination processes to make them powered by solar energy.
- Presently CO_2 contribution from desalination plants is about 0.3% of total CO_2 load to atmosphere. Renewable energy is environmentally friendly.
- Current trend in fossil fuel cost increase and developments in solar collectors may make the solar desalination a feasible option for large scale application in the future.
- Presently solar desalination can be used for small/medium scale applications in remote locations where electricity grid is not available.
- More R&D is needed to improve desalination systems coupled with renewable energy technologies and to reduce the cost of desalinated water.
- Technical improvements and further developments will make renewable energy contributing much more.

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